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The Case for a Kilometer-Scale High Energy Neutrino Detector[*]

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Doing astronomy with photons of energies in excess of a GeV has turned out to be extremely challenging. Efforts are underway to develop instruments that may push astronomy to wavelengths smaller than 10^{-14} cm by mapping the sky in high energy neutrinos instead. Neutrino astronomy, born with the identification of thermonuclear fusion in the sun and the particle processes controlling the fate of a nearby supernova, will reach outside the galaxy and make measurements relevant to cosmology. The field is immersed in technology in the domains of particle physics to which many of its research goals are intellectually connected. To mind come the search for neutrino mass, cold dark matter (supersymmetric particles?) and the monopoles of the Standard Model. While a variety of collaborations are pioneering complementary methods by building telescopes with effective area in excess of 0.01 km^2, we show here that the natural scale of a high energy neutrino telescope is 1 km^2. With several thousand optical modules and a price tag unlikely to exceed 100 million dollars, the scope of a kilometer-scale instrument is similar to that of experiments presently being commissioned such as the SNO neutrino observatory in Canada and the Superkamiokande experiment in Japan.

INTRODUCTION

The photon sky has been probed with a variety of instruments sensitive to wavelengths of light as large as 10^4 cm for radio-waves to 10^{-14} cm for the GeV-photons detected with space-based instruments. Astronomical instruments have now collected data spanning 60 octaves in photon frequency, an amazing expansion of the power of our eyes which scan the sky over less than a single octave just above 10^{-7} cm. Doing gamma ray astronomy at TeV energies and beyond has, however, turned out to be a considerable challenge. Not only are the fluxes expected to be small, as one can demonstrate by extrapolating measured photon fluxes of MeV and GeV sources, they are dwarfed by a flux of cosmic ray particles which is larger by typically two orders of magnitude. The discoveries of the Crab supernova remnant and the active galaxy Markarian 421 at TeV-energy have proven that the problems are not insurmountable, more about that later. They are, however, sufficiently daunting to have encouraged a vigorous effort to probe the high energy sky by detecting neutrinos instead.

It is important to realize that high energy photons, unlike weakly interacting neutrinos, do not carry information on any cosmic sites shielded from our view by more than a few hundred grams of intervening matter. The TeV-neutrino could reveal objects with no counterpart in any wavelength of light. High energy neutrinos are the decay products of pions and are therefore a signature of the most energetic cosmic processes. Their energy exceeds those of neutrinos artificially produced at existing or planned accelerators. As was the case with radiotelescopes, for instance, unexpected discoveries could be made. Forays into new wavelength regimes have historically led to the discovery of unanticipated phenomena. As is the case with new accelerators, observing the predictable will be slightly disappointing. Neutrino telescopes have the advantage of looking at a large fraction of the sky all the time, an important astronomical advantage over gamma ray detectors such as Cherenkov telescopes which can at best scan a few degrees of the sky 10% of the time. The natural background for observing cosmic neutrinos in the TeV range and above consists of atmospheric neutrinos which are the decay products of pions produced in cosmic ray-induced atmospheric cascades. We will see that the expected sources actually dominate the neutrino sky in stark contrast to the situation, previously mentioned, where the cosmic ray flux exceeds those from high energy gamma sources by orders of magnitude.

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1. GUARANTEED COSMIC NEUTRINO BEAMS

In heaven, as on Earth, high energy neutrinos are produced in beam dumps which consist of a high energy proton (or heavy nucleus) accelerator and a target in which gamma rays and neutrinos are generated in roughly equal numbers in the decays of pions produced in nuclear cascades in the beam dump. For every π^0 producing two gamma rays, there is a charged π^+ and π^- decaying into $\mu^+\nu_\mu$. As a rule of thumb the dump produces one neutrino for each interacting proton. If the kinematics is such that muons decay in the dump, more neutrinos will be produced. It should be stressed immediately that in efficient cosmic beam dumps with an abundant amount of target material, high energy photons may be absorbed before escaping the source. Therefore, the most spectacular neutrino sources may have no counterpart in high energy gamma rays.

By their very existence, high-energy cosmic rays do guarantee the existence of definite sources of high energy cosmic neutrinos[1]. They represent a beam of known luminosity with particles accelerated to energies in excess of 10^{20} eV. Cosmic rays produce pions in interactions with i) the interstellar gas in our galaxy, ii) the cosmic photon background, iii) the sun and, finally, iv) the Earth's atmosphere which represents a well-understood beam dump. These interactions are the source of fluxes of diffuse photons and neutrinos. The atmospheric neutrino beam is well understood and can be used to study neutrino oscillations over oscillation lengths varying between 10 and 10^4 km[1].

A rough estimate of the diffuse fluxes of gamma rays and neutrinos from the galactic disk can be obtained by colliding the observed cosmic ray flux with interstellar gas with a nominal density of 1 proton per cm^3. The target material is concentrated in the disk of the galaxy and so will be the secondary photon flux. The gamma ray flux has been identified by space-borne gamma ray detectors. It is clear that a roughly equal diffuse neutrino flux is produced by the decay of charged pion secondaries in the same collisions. Conservatively, assuming a detector threshold of 1 TeV one predicts three neutrino-induced muons per year in a 10^6 m^2 detector from a solid angle

of 0.07 sr around the direction of Orion. There are several concentrations of gas with similar or smaller density in the galaxy. The corresponding number of neutrino events from within 10 degrees of the galactic disc is 50 events per year for a 10^6 m^2 detector at the South Pole which views 1.1 steradian of the outer Galaxy with an average density of 0.013 grams/cm^2.

A guaranteed source of extremely energetic diffuse neutrinos is the interaction of ultra high energy, extra-galactic, cosmic rays on the microwave background. The major source of energy loss is photoproduction of the Δ resonance by the cosmic proton beam on a target of background photons with a density of $\sim$400 photons/cm^3 and an average energy of

$$\epsilon = 2.7 \times k_B \times 2.735° \simeq 7 \times 10^{-4} \text{ eV} . \qquad (1)$$

For cosmic ray energies exceeding

$$E_p \approx \frac{m_\Delta^2 - m_p^2}{2(1-\cos\theta)\epsilon} \approx \frac{5 \times 10^{20}}{(1-\cos\theta)} \text{ eV} , \qquad (2)$$

where θ is the angle between the proton and photon directions, the photopion cross-section grows very rapidly to reach a maximum of 540 μb at the Δ^+ resonance ($s = 1.52$ GeV^2). The Δ^+ decays to $p\pi^0$ with probability of 2/3, and to $n\pi^+$ with probability 1/3. The charged pions are the source of very high energy muon-neutrino fluxes as a result of decay kinematics where each neutrino takes approximately 1/4 of the parent pion energy. In addition neutrons decay producing a flux of lower energy $\bar\nu_e$.

The magnitude and intensity of the cosmological neutrino fluxes is determined by the maximum injection energy of the ultra-high-energy cosmic rays and by the distribution of their sources. If the sources are relatively near at distances of order tens of Mpc, and the maximum injection energy is not much greater than the highest observed cosmic ray energy (few $\times 10^{20}$ eV), the generated neutrino fluxes are small. If, however, the highest energy cosmic rays are generated by many sources at large redshift, then a large fraction of their injection energy would be presently contained in γ-ray and neutrino fluxes. The reason is that the energy density of the microwave radiation as well as the photoproduction cross-section scale as $(1+z)^4$. The effect would be even

stronger if the source luminosity were increasing with z, i.e. cosmic ray sources were more active at large redshifts – 'bright phase' models. Early speculations on bright phase models led to the suggestion of kilometer-scale neutrino detectors over a decade ago[2].

The other guaranteed extraterrestrial source of high energy neutrinos is the Sun. The production process is exactly the same as for atmospheric neutrinos on Earth: cosmic ray interactions in the solar atmosphere. Neutrino production is enhanced because the atmosphere of the Sun is much more tenuous. The scaleheight of the chromosphere is $\sim$115 km, compared with 6.3 km for our upper atmosphere. A detailed calculation of the neutrino production by cosmic rays in the solar atmosphere shows a neutrino spectrum larger than the angle averaged atmospheric flux by a factor of $\sim$2 at 10 GeV and a factor of $\sim$3 at 1000 GeV. The decisive factor for the observability of this neutrino source is the small solid angle (6.8×10^{-5} sr) of the Sun. Although the rate of the neutrino induced upward going muons is higher than the atmospheric emission from the same solid angle by a factor of $\sim$5, the rate of muons of energy above 10 GeV in a 10^6 m^2 detector is only 50 per year. Taking into account the diffusion of the cosmic rays in the solar wind, which decreases the value of the flux for energies below one TeV, cuts this event rate by a factor of 3. Folded with a realistic angular resolution of 1 degree, observation of such an event rate requires, as for the previous examples, a 1 km^2 detector.

2. ACTIVE GALACTIC NUCLEI: ALMOST GUARANTEED?

Although observations of PeV (10^{15} eV) and EeV (10^{18} eV) gamma-rays are controversial, cosmic rays of such energies do exist and their origin is at present a mystery. The cosmic-ray spectrum can be understood, up to perhaps 1000 TeV, in terms of shockwave acceleration in galactic supernova remnants. Although the spectrum suddenly steepens at 1000 TeV, a break usually referred to as the "knee", cosmic rays with much higher energies are observed and cannot be accounted for by this mechanism. This failure can be understood by simple dimensional analysis because the EMF

in the supernova shock is of the form

$$E = ZeBRc, \tag{3}$$

where B and R are the magnetic field and the radius of the shock. For a proton Eq. (3) yields a maximum energy

$$E_{\max} = \left[10^5 \, \text{TeV}\right] \left[\frac{B}{3 \times 10^{-6} \, \text{G}}\right] \left[\frac{R}{50 \, \text{pc}}\right] \tag{4}$$

and therefore E is less than 10^5 TeV for the typical values of B, R shown. The actual upper limit is much smaller than the value obtained by dimensional analysis because of inefficiencies in the acceleration process.

Cosmic rays with energy in excess of 10^{20} eV have been observed. Assuming that they are a galactic phenomenon, the measured spectrum implies that 10^{34} particles are accelerated to 1000 TeV energy every second. We do not know where or how. We do not know whether the particles are protons or iron or something else. If the cosmic accelerators indeed exploit the 3μGauss field of our galaxy, they must be much larger than supernova remnants in order to reach 10^{21} eV energies. Equation (3) requires that their size be of order 30 kpc. Such an accelerator exceeds the dimensions of our galaxy. Although imaginative arguments exist to avoid this impasse, an attractive alternative is to look for large size accelerators outside the galaxy. Nearby active galactic nuclei (quasars, blazars...) distant by order 100 Mpc are the obvious candidates. With magnetic fields of tens of μGauss over distances of kpc near the central black hole or in the jets, acceleration to 10^{21} eV is possible; see Eq. (3).

One can visualize the accelerator in a very economical way in the Blanford-Zralek mechanism. Imagine that the horizon of the central black hole acts as a rotating conductor immersed in an external magnetic field. By simple dimensional analysis this creates a voltage drop

$$\frac{\Delta V}{10^{20} \text{volts}} = \frac{a}{M_{\text{BH}}} \frac{B}{10^4 \text{G}} \frac{M_{\text{BH}}}{10^9 M_\odot} \,, \tag{5}$$

corresponding to a luminosity

$$\frac{\mathcal{L}}{10^{45} \text{erg s}^{-1}} = \left(\frac{a}{M_{\text{BH}}}\right)^2 \left(\frac{B}{10^4 \text{G}}\right)^2 \left(\frac{M_{\text{BH}}}{10^9 M_\odot}\right)^2. \tag{6}$$

Here a is the angular momentum per unit mass of a black hole of mass M_{BH}.

All this was pretty much a theorist's pipe dream until recently the Whipple collaboration reported the observation of TeV (10^{12} eV) photons from the giant elliptical galaxy Markarian 421[3]. With a signal in excess of 6 standard deviations, this was the first convincing observation of TeV gamma rays from outside our Galaxy. That a distant source such as Markarian 421 can be observed at all implies that its luminosity exceeds that of galactic cosmic accelerators such as the Crab, the only source observed by the same instrument with comparable statistical significance, by close to 10 orders of magnitude. More distant by a factor 10^5, the instrument's solid angle for Markarian 421 is reduced by 10^{-10} compared to the Crab. Nevertheless the photon count at TeV energy is roughly the same for the two sources. The Whipple observation implies a Markarian 421 photon luminosity in excess of 10^{43} ergs per second. It is interesting that these sources have their highest luminosity above TeV energy, beyond the wavelengths of conventional astronomy. During May 1994 observations of the flux of Markarian 421 was observed to increase by a factor 10 in one day, strongly suggesting the catastrophic operation of a high energy hadronic accelerator.

Why Markarian 421? Whipple obviously zoomed in on the Compton Observatory catalogue of active galaxies (AGNs) known to emit GeV photons. Markarian, at a distance of barely over 100 Mpc, is the closest blazar on the list. As yet TeV gamma rays have not been detected from any other AGNs. Although Markarian 421 is the closest of these AGNs, it is one of the weakest; the reason that it is detected whereas other, more distant, but more powerful, AGNs are not, must be that the TeV gamma rays suffer absorption in intergalactic space through the interaction with background infra-red photons. TeV gamma rays are indeed efficiently absorbed on infra-red starlight and this most likely provides the explanation why astronomers have a hard time observing much more powerful quasars such as 3C279 at a redshift of 0.54. Production of e^+e^- pairs by TeV gamma rays interacting with IR background photons is the origin of the absorption. The absorption is, however, minimal for Mrk 421 with $z = 0.03$, a distance close enough to see through the IR fog. This implies that all of the AGNs may have significant very high energy components but that only Markarian 421 is close enough to be detectable with currently available gamma-ray telescopes.

This observation was not totally unanticipated. Many theorists[1] have identified blazars such as Markarian 421 as powerful cosmic accelerators producing beams of very high energy photons and neutrinos. Acceleration of particles is by shocks in the jets (or, possibly, also by shocks in the accretion flow onto the supermassive black hole which powers the galaxy) which are a characteristic feature of these radio-loud active galaxies. Many arguments have been given for the acceleration of protons as well as electrons. Inevitably beams of gamma rays and neutrinos from the decay of pions appear along the jets. The pions are photoproduced by accelerated protons on the target of optical and UV photons in the galaxy which reaches densities of 10^{14} per cm^3. The latter are the product of synchrotron radiation by electrons accelerated along with the protons.

Powerful AGNs at distances of order 100 Mpc and with proton luminosities of 10^{45} erg/s or higher are obvious candidates for the cosmic accelerators of the highest energy cosmic rays. Their luminosity often peaks at the highest energies and their proton flux, propagated to Earth, can quantitatively reproduce the cosmic ray spectrum above spectrum 10^{18} eV[4]. Some have argued that all cosmic rays above the "knee" in the spectrum at 10^{15} eV may be of AGN origin. The neutrino flux from such accelerators can be calculated by energy conservation:

$$\mathcal{L}_p N \epsilon_{\text{eff}} = 4\pi d^2 \int dE [E \, dN_\nu/dE] \, , \qquad (7)$$

where N_ν is the neutrino flux at Earth, d the average distance to the sources, N the number of sources and ϵ_{eff} the efficiency for protons to produce pions (or neutrinos, assuming the production of 1 neutrino per interacting proton) in the AGN beamdump. This yields

$$E \frac{dN_\nu}{dE} = \frac{N \epsilon_{\text{eff}}}{4\pi} \frac{7.5 \times 10^{-10}}{E \, (\text{TeV})} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \qquad (8)$$

for $\mathcal{L}_p = 10^{45}$ erg/s and $d = 100$ Mpc. We here assumed an E^{-2} energy spectrum extending to 10^{20} eV energy. With ϵ_{eff} of order 10^{-1} to 10^{-3}

and the number of relatively nearby sources N in the range 10 to 1000, it is a reasonable estimate that $N\epsilon_{\text{eff}} = 1$. The total energy in excess of 1 EeV (10^{18}-10^{20} eV) is 5×10^{-9} erg/cm^2/s. This number nicely matches the energy density of the extra-galactic cosmic rays in the same interval of energy as it should assuming, again, that 1 neutrino is produced for every proton in the AGN dump. The flux of Eq. (8) is at the low end of the range of fluxes predicted by Biermann et al. and by Protheroe et al. and Stecker et al. in models where acceleration is in shocks in the jet[4] and accretion disc[5, 6], respectively.

The above discussion suggests a very simple estimate of the AGN neutrino flux that finesses all guesses regarding the properties of individual sources:

$$4\pi \int_{10^{17} \text{ eV}} dE[E\, dN_\nu/dE] \simeq \mathcal{L}_{\text{CR}}$$
$$\simeq 7.2 \times 10^{-9} \,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1} \,, \tag{9}$$

which simply states that AGNs generate 1 neutrino for each proton. $\mathcal{L}_{\text{CR}}$ is obtained by integrating the highest energy $E^{-2.71}$ component of the cosmic ray flux above 10^{17} eV. Assuming an E^{-2} neutrino spectrum we recover the result of Eq. (8). Is is now clear that our flux is a lower limit as protons should be absorbed in ambient matter in the source or in the interstellar medium.

3. INTERMEZZO: THE CASE FOR A KILOMETER-SCALE DETECTOR

Observing AGNs has become a pivotal goal in the development of high energy neutrino telescopes. Neutrinos are observed via the muons they produce in the detector volume. At high energy it is possible to enhance the effective volume of detectors by looking for neutrino-induced muons generated in charged-current interactions of ν_μ in the water or ice outside the instrumented detector volume. The effective detector volume is then the product of the detector area and the muon range in rock R$_\mu$. TeV muons have a typical range of one kilometer, which leads to a significant increase in effective detector volume. The average muon energy loss rate is

$$\left\langle \frac{dE}{dX} \right\rangle = -\alpha(E) - \beta(E) \times E \,, \tag{10}$$

where X is the thickness of material in g/cm^2. The first term represents ionization losses, which are approximately independent of energy, with $\alpha \sim 2$ MeV g^{-1}cm^2. The second term includes the catastrophic processes of bremsstrahlung, pair production and nuclear interactions, for which fluctuations play an essential role. Here $\beta \sim 4 \times 10^{-6}$ g^{-1}cm^2. The critical energy above which the radiative processes dominate is

$$E_{\text{cr}} = \alpha/\beta \approx 500\,\text{GeV}. \tag{11}$$

To treat muon propagation properly when $E_\mu > E_{\text{cr}}$ requires a Monte Carlo calculation of the probability P_{surv} that a muon of energy E_μ survives with energy $> E_\mu^{\text{min}}$ after propagating a distance X. The probability that a neutrino of energy E_ν on a trajectory through a detector produces a muon above threshold at the detector is

$$P_\nu(E_\nu, E_\mu^{\text{min}}) = N_A \int_0^{E_\nu} dE_\mu \frac{d\sigma_\nu}{dE_\mu}(E_\mu, E_\nu) \\ \times R_{\text{eff}}(E_\mu, E_\mu^{\text{min}}) \,, \tag{12}$$

where

$$R_{\text{eff}} = \int_0^\infty dX\, P_{\text{surv}}(E_\mu, E_\mu^{\text{min}}, X) \,. \tag{13}$$

The flux of ν_μ-induced muons at the detector is given by a convolution of the neutrino spectrum ϕ_ν with the muon production probability (12) as

$$\phi_\mu(E_\mu^{\text{min}}, \theta) = \int_{E_\mu^{\text{min}}} \left\{ dE_\nu\, P_\nu(E_\nu, E_\mu^{\text{min}}) \right. \\ \left. \times \exp[-\sigma_{\text{t}}(E_\nu)\, X(\theta)\, N_A]\, \phi_\nu(E_\nu, \theta) \right\} \,. \tag{14}$$

The exponential factor here accounts for absorption of neutrinos along the chord of the Earth, $X(\theta)$. Absorption becomes important for $\sigma(E_\nu) \gtrsim 10^{-33}$ cm^2 or $E_\nu \gtrsim 10^7$ GeV.

The event rate in a detector is obtained by multiplying Eq. (14) by its effective area. From Eqs. (8),(14) we obtain order 300 upcoming muon events per year in a 10^6 m^2 detector. It is not a comfortably large rate however as the flux is indeed distributed over a large number of sources. There is, however, no competing background. Hopefully one will be able to scrutinize a few nearby sources with good statistics. We should recall at this point that our back-of-the-envelope estimate yields a flux at the lower end of the range

of fluxes predicted by detailed modeling. Optimistic predictions exceed our estimate by over an order of magnitude and are, possibly, within reach of the telescopes now being commissioned.

The neutrino sky at GeV-energy and above is summarized in Fig. 1. Shown is the flux from the galactic plane as well as a range of estimates (from generous to conservative) for the diffuse fluxes of neutrinos from active galaxies and from the interaction of extra-galactic cosmic rays with cosmic photons. At PeV energies and above all sources dominate the background of atmospheric neutrinos. In order to deduce the effective area of an instrument required to study the fluxes in the figure, the detection efficiency must be included using Eq. (14). At the highest energies this efficiency approaches unity and 1 event per km^2 per year corresponds to the naive estimate of 10^{-18} neutrinos per cm^2 second. At TeV–PeV energy the one event level per year corresponds to a flux of 10^{-14}–10^{-15} per cm^2 second. As before, we conclude that the diffuse flux from AGN yields order 10^3 events in a kilometer-size detector per year in the TeV-energy range.
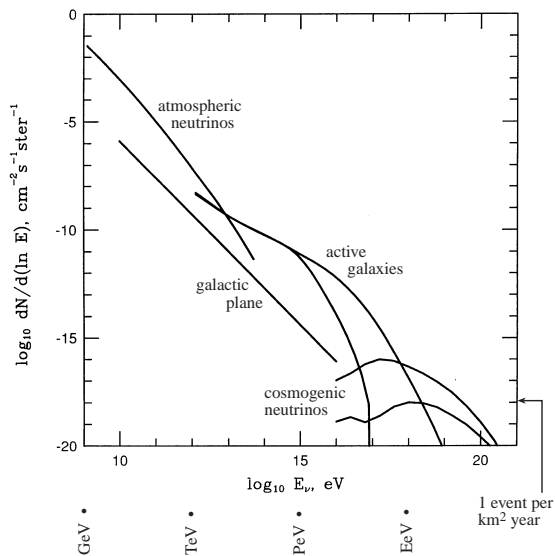

Fig. 1

It should be emphasized that high energy neutrino detectors are multi-purpose instruments. Their science-reach touches astronomy, astrophysics and particle physics. Further motivations for the construction of a km^3 deep underground detector include[1]:

1. The search for the t'Hooft-Polyakov monopoles predicted by the Standard Model.

2. The study of neutrino oscillations by monitoring the atmospheric neutrino beam. One can exploit the unique capability of relatively shallow neutrino telescopes, i.e. detectors positioned at a depth of roughly 1 km, to detect neutrinos and muons of similar energy. In a ν_μ oscillation experiment one can therefore tag the π progenitor of the neutrino by detecting the muon produced in the same decay. This eliminates the model dependence of the measurement inevitably associated with the calculation of the primary cosmic ray flux. Surface neutrino telescopes probe the parameter space $\Delta m^2 \gtrsim 10^{-3}$ eV^2 and $\sin^2 2\theta \gtrsim 10^{-3}$ using this technique. Recently underground experiments have given tantalizing hints for neutrino oscillations in this mass range.

3. The search for neutrinos from the annihilation of dark matter particles in our galaxy.

4. The capability to observe the thermal neutrino emission from supernovae[7] (even though the nominal threshold of the detectors exceeds the neutrino energy by several orders of magnitude!). The detector will be able to monitor our galaxy over decades in a most economical fashion.

5. Further study of the science pioneered by space-based gamma ray detectors such as the study of gamma ray bursts and the high energy emission from quasars.

It is intriguing that each of these goals point individually at the necessity to commission a kilometer-size detector. In order to illustrate this I will discuss the search for the particles which constitute the cold dark matter.

4. INDIRECT SEARCH FOR COLD DARK MATTER

It is believed that most of our Universe is made of cold dark matter particles. Big bang cosmology implies that these particles have interactions of order the weak scale, i.e. they are WIMPs[8]. We know everything about these particles except

whether they really exist. We know that their mass is of order of the weak boson mass, we know that they interact weakly. We also know their density and average velocity in our galaxy as they must constitute the dominant component of the density of our galactic halo as measured by rotation curves. WIMPs will annihilate into neutrinos with rates whose estimate is straightforward. Massive WIMPs will annihilate into high energy neutrinos. Their detection by high energy neutrino telescopes is greatly facilitated by the fact that the sun, conveniently, represents a dense and nearby source of cold dark matter particles.

Galactic WIMPs, scattering off protons in the sun, lose energy. They may fall below escape velocity and be gravitationally trapped. Trapped dark matter particles eventually come to equilibrium temperature, and therefore to rest at the center of the sun. While the WIMP density builds up, their annihilation rate into lighter particles increases until equilibrium is achieved where the annihilation rate equals half of the capture rate. The sun has thus become a reservoir of WIMPs which annihilate into any open fermion, gauge boson or Higgs channels. The leptonic decays from annihilation channels such as $b\bar{b}$ heavy quark and W^+W^- pairs turn the sun into a source of high energy neutrinos. Their energies are in the GeV to TeV range, rather than in the familiar KeV to MeV range from its thermonuclear burning. These neutrinos can be detected in deep underground experiments.

We illustrate the power of neutrino telescopes as dark matter detectors using as an example the search for a 500 GeV WIMP with a mass outside the reach of present accelerator and future LHC experiments. A quantitative estimate of the rate of high energy muons of WIMP origin triggering a detector can be made in 5 easy steps.

Step 1: The halo neutralino flux ϕ_χ.
It is given by their number density and average velocity. The cold dark matter density implied by the observed galactic rotation curves is $\rho_\chi = 0.4$ GeV/cm^3. The galactic halo is believed to be an isothermal sphere of WIMPs with average velocity $v_\chi = 300$ km/sec. The number density is then

$$n_\chi = 8 \times 10^{-4} \left[\frac{500 \text{ GeV}}{m_\chi} \right] \text{ cm}^{-3} \tag{15}$$

and therefore

$$\phi_\chi = n_\chi v_\chi = 2 \times 10^4 \left[\frac{500 \text{ GeV}}{m_\chi} \right] \text{ cm}^{-2} \text{s}^{-1}. \tag{16}$$

Step 2: Cross section σ_{sun} for the capture of neutralinos by the sun.
The probability that a WIMP is captured is proportional to the number of target hydrogen nuclei in the sun (i.e. the solar mass divided by the nucleon mass) and the WIMP-nucleon scattering cross section. From dimensional analysis $\sigma(\chi N) \sim \left(G_F m_N^2 \right)^2 / m_Z^2$ which we can envisage as the exchange of a neutral weak boson between the WIMP and a quark in the nucleon. The main point is that the WIMP is known to be weakly interacting. We obtain for the solar capture cross section

$$\begin{aligned} \Sigma_{\text{sun}} = n\sigma &= \frac{M_{\text{sun}}}{m_N}\sigma(\chi N) \\ &= \left[1.2 \times 10^{57} \right] \left[10^{-41} \text{ cm}^2 \right]. \end{aligned} \tag{17}$$

Step 3: Capture rate N_{cap} of neutralinos by the sun.
N_{cap} is determined by the WIMP flux (16) and the sun's capture cross section (17) obtained in the first 2 steps:

$$N_{\text{cap}} = \phi_\chi \Sigma_{\text{sun}} = 3 \times 10^{20} \text{ s}^{-1}. \tag{18}$$

Step 4: Number of solar neutrinos of dark matter origin.
The sun comes to a steady state where capture and annihilation of WIMPs are in equilibrium. For a 500 GeV WIMP the dominant annihilation rate is into weak bosons; each produces muon-neutrinos with a branching ratio which is roughly 10%:

$$\chi\bar{\chi} \rightarrow WW \rightarrow \mu\nu_\mu. \tag{19}$$

Therefore, as we get 2 W's for each capture, the number of neutrinos generated in the sun is

$$N_\nu = \frac{1}{5} N_{\text{cap}} \tag{20}$$

and the corresponding neutrino flux at Earth is given by

$$\phi_\nu = \frac{N_\nu}{4\pi d^2} = 2 \times 10^{-8} \text{ cm}^{-2}\text{s}^{-1}, \tag{21}$$

where the distance d is 1 astronomical unit.

Step 5: Event rate in a high energy neutrino telescope.

For (19) the W-energy is approximately m_χ and the neutrino energy half that by two-body kinematics. The energy of the detected muon is given by

$$E_\mu \simeq \frac{1}{2} E_\nu \simeq \frac{1}{4} m_\chi \,. \qquad (22)$$

Here we used the fact that, in this energy range, roughly half of the neutrino energy is transferred to the muon. Simple estimates of the neutrino interaction cross section and the muon range can be obtained as follows

$$\sigma_{\nu \to \mu} = 10^{-38}\,\mathrm{cm}^2\,\frac{E_\nu}{\mathrm{GeV}} = 2.5 \times 10^{-36}\,\mathrm{cm}^2 \quad (23)$$

and

$$R_\mu = 5\ \mathrm{m}\,\frac{E_\mu}{\mathrm{GeV}} = 625\ \mathrm{m}\,, \qquad (24)$$

which is the distance covered by a muon given that it loses 2 MeV for each gram of matter traversed. We have now collected all the information to compute the number of events in a detector of area $10^4\,\mathrm{m}^2$, typical for those presently under construction.

For the neutrino flux given by (21) we obtain

$$\# \,\mathrm{events/year} = 10^6 \times \phi_\nu \times \rho_{\mathrm{H_2O}} \times \sigma_{\nu \to \mu} \times R_\mu$$
$$\simeq 1000 \qquad (25)$$

for a 1 km^2 water Cherenkov detector, where R_μ is the muon range and $\phi_\nu \times \rho_{\mathrm{H_2O}} \times \sigma_{\nu \to \mu}$ is the analog of Eq. (14).

The above exercise is just meant to illustrate that high energy neutrino telescopes compete with present and future accelerator experiments in the search for dark matter and supersymmetry; see below. The above exercise can be repeated as a function of WIMP mass. The result is shown in Fig. 2 (the two branches as well as the structure in the curves are related to details of supersymmetry. These are, for all practical purposes, irrelevant). Especially for heavier WIMPs the technique is very powerful because underground high energy neutrino detectors have been optimized to be sensitive in the energy region where the neutrino interaction cross section and the range of the muon are large. Also, for high energy neutrinos the muon and
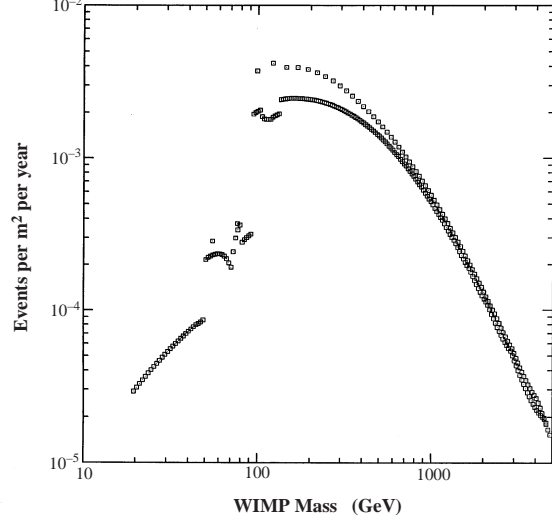

Fig. 2

neutrino are aligned along a direction pointing back to the sun with good angular resolution. A kilometer-size detector probes WIMP masses up to the TeV-range beyond which they are excluded by cosmological considerations. The technique fails for low masses only for those mass values already excluded by unsuccessful accelerator searches. Competitive direct searches for dark matter will have to deliver detectors reaching better than 0.05 events/kg/day sensitivity.

Particle physics provides us with rather compelling candidates for WIMPs. The Standard Model is not a model: its radiative corrections are not under control. A most elegant and economical way to revamp it into a consistent and calculable framework is to make the model supersymmetric. If supersymmetry is indeed Nature's extension of the Standard Model it must produce new phenomena at or below the TeV scale. A very attractive feature of supersymmetry is that it provides cosmology with a natural dark matter candidate in form of a stable lightest supersymmetric particle[8]. This is, in fact, the only candidate because supersymmetry completes the Standard Model all the way to the GUT scale where its forces apparently unify. Because supersymmetry logically completes the Standard Model with no other new physics threshold up to the GUT-scale, it must supply the dark matter. So, if supersymmetry, dark matter and accelerator detectors are on a level playing field. The interpretation of

above arguments in the framework of supersymmetry are explicitly stated in Ref. [9].

5. DUMAND ET AL.: COMPLEMENTARY TECHNOLOGIES

We have presented arguments for doing neutrino astronomy on the scale of 1 kilometer. In order to achieve large effective area it is, unfortunately, necessary to abandon the low MeV thresholds of detectors such as IMB and Kamiokande. One focuses on high energies where: i) neutrino cross sections are large and the muon range is increased; see Equation (14), ii) the angle between the muon and parent neutrino is less than 1 degree and, iii) the atmospheric neutrino background is small. The accelerator physicist's method for building a neutrino detector uses absorber, chambers with a few x, y wires and associated electronics with a price of roughly 10^4 US dollars per m^2. Such a 1 km^2 detector would cost 10 billion dollars. Realistically, we are compelled to develop methods which are more cost-effective by a factor 100 in order to be able to commission neutrino telescopes with area of order 1 km^2. Obviously, the proven technique developed by IMB, Kamiokande and others cannot be extrapolated to kilometer scale. All present telescopes do however exploit the well-proven Cherenkov technique.

In a Cherenkov detector the direction of the neutrino is inferred from the muon track which is measured by mapping the associated Cherenkov cone travelling through the detector. The arrival times and amplitudes of the Cherenkov photons, recorded by a grid of optical detectors, are used to reconstruct the direction of the radiating muon. The challenge is well-defined: record the muon direction with sufficient precision (i.e., sufficient to reject the much more numerous down-going cosmic ray muons from the up-coming muons of neutrino origin) with a minimum number of optical modules (OM). Critical parameters are detector depth which determines the level of the cosmic ray muon background and the noise rates in the optical modules which will sprinkle a muon trigger with false signals. Sources of such noise include radioactive decays such as potassium decay in water, bioluminescence and, inevitably, the dark current of the photomultiplier tube. The

experimental advantages and challenges are different for each experiment and, in this sense, they nicely complement one another as engineering projects for a large detector. Each has its own "gimmick" to achieve neutrino detection with a minimum number of OMs:

1. AMANDA uses sterile ice, free of radioactivity;
2. Baikal triggers on pairs of OMs;
3. DUMAND and NESTOR shield their arrays by over 4 km of ocean water.

Detectors under construction will have a nominal effective area of 10^4 m^2. The OMs are deployed like beads on strings separated by 20–50 meters. There are typically 20 OMs per string separated by roughly 10 meters. Baikal is presently operating 36 optical modules, 18 pointing up and 18 down, and the South Pole AMANDA experiment started operating 4 strings with 20 optical modules each in January 94. The first generation telescopes will consist of roughly 200 OMs. Briefly,

1. AMANDA is operating in deep clear ice with an absorption length in excess of 60 m similar to that of the clearest water used in the Kamiokande and IMB experiments. The ice provides a convenient mechanical support for the detector. The immediate advantage is that all electronics can be positioned at the surface. Only the optical modules are deployed into the deep ice. Polar ice is a sterile medium with a concentration of radioactive elements reduced by more than 10^{-4} compared to sea or lake water. The low background results in an improved sensitivity which allows for the detection of high energy muons with very simple trigger schemes which are implemented by off-the-shelf electronics. Being positioned under only 1 km of ice it is operating in a cosmic ray muon background which is over 100 times larger than deep-ocean detectors such as DUMAND. The challenge is to reject the down-going muon background relative to the up-coming neutrino-induced muons by a factor larger than 10^6. The group claims to have met this challenge with an

up/down rejection which is similar to that of the deep detectors.

Although residual bubbles are found at depth as large as 1 km, their density decreases rapidly with depth. Ice at the South Pole should be bubble-free below 1100–1300 m as it is in other polar regions. The effect of bubbles on timing of photons has been measured by the laser calibration system deployed along with the OMs. After taking the scattering of the light on bubbles into account reconstruction of muons has been demonstrated by a successful measurement of the characteristic fluxes of cosmic ray muons.

The polar environment turned out to be surprisingly friendly but only allows for restricted access and one-shot deployment of photomultiplier strings. The technology has, however, been satisfactorily demonstrated with the deployment of the first 4 strings. It is clear that the hot water drilling technique can be used to deploy OM's larger than the 8 inch photomultiplier tubes now used to any depth in the 3 km deep ice cover. AMANDA will deploy 6 more strings in 1995 at a depth of 1500 meters.

2. BAIKAL shares the shallow depth of AMANDA and large background counting rate of tens of kHz from bioluminescence and radioactive decays with DUMAND. It suppresses its background by pairing OMs in the trigger. Half its optical modules are pointing up in order to achieve a uniform acceptance over upper and lower hemispheres. The depth of the lake is 1.4 km, so the experiment cannot expand downwards and will have to grow horizontally.

The Baikal group has been operating an array of 18(36) Quasar photomultiplier (a Russian-made 15 inch tube) units deployed in April 1993(94). They have reached a record up/down rejection ratio of 10^{-4} and, according to Monte Carlo, will reach the 10^{-6} goal to detect neutrinos as soon as the full complement of 200 OMs is deployed. They expect to deploy 97 additional OMs in 1995.

3. DUMAND will be positioned under 4.5 km of ocean water, below most biological activity and well shielded from cosmic ray muon backgrounds. A handicap of using ocean water is the background light resulting from radioactive decays, mostly K^{40}, plus some bioluminescence, yielding a noise rate of 60 kHz in a single OM. Deep ocean water is, on the other hand very clear, with an attenuation length of order 40 m in the blue. The deep ocean is a difficult location for access and service. Detection equipment must be built to high reliability standards, and the data must be transmitted to the shore station for processing. It has required years to develop the necessary technology and learn to work in an environment foreign to high-energy physics experimentation, but hopefully this will be accomplished satisfactorily.

The DUMAND group has successfully analysed data on cosmic ray muons from the deployment of a test string. They have already installed the 25 km power and signal cables from detector to shore as well as the junction box for deploying the strings. The group will proceed with the deployment of 3 strings in 1995.

4. NESTOR is similar to DUMAND, being placed in the deep ocean (the Mediterranean), except for two critical differences. Half of its optical modules point up, half down like Baikal. The angular response of the detector is being tuned to be much more isotropic than either AMANDA or DUMAND, which will give it advantages in, for instance, the study of neutrino oscillations. Secondly, NESTOR will have a higher density of photocathode (in some substantial volume) than the other detectors, and will be able to make local coincidences on lower energy events, even perhaps down to the supernova energy range (tens of MeV).

5. Other detectors have been proposed for near surface lakes or ponds (e.g. GRANDE, LENA, NET, PAN and the Blue Lake Project), but at this time none are in construction[10]. These detectors all would have the great advantage of accessibility

and ability for dual use as extensive air shower detectors, but suffer from the 10^{10}–10^{11} down-to-up ratio of muons, and face great civil engineering costs (for water systems and light-tight containers). Even if any of these are built it would seem that the costs may be too large to contemplate a full kilometer-scale detector.

6. SKETCH OF A KILOMETER-SIZE DETECTOR

In summary, there are four major experiments proceeding with construction, each of which has different strengths and faces different challenges. For the construction of a 1 km scale detector one can imagine any of the above detectors being the basic building block for the ultimate 1 km^3 telescope. The redesigned AMANDA detector (with spacings optimized to the absorption length of 60 m), for example, consists of 5 strings on a circle of 60 meter radius around a string at the center (referred to as a $1 + 5$ configuration). Each string contains 13 OMs separated by 15 m. Its effective volume for TeV-neutrinos is just below 10^7 m^3. Imagine AMANDA "supermodules" which are obtained by extending the basic string length (and module count per string) by a factor close to 4. Supermodules would then consist of $1 + 5$ strings with 51 OMs separated by 20 meters on each string, for a total length of 1 km. A 1 km scale detector then may consist of a $1+7+7$ configuration of supermodules, with the 7 supermodules distributed on a circle of radius 250 m and 7 more on a circle of 500 m. The full detector then contains 4590 phototubes, which is less than the 9000 used in the SNO detector. Such a detector (see Fig. 3) can be operated in a dual mode:

1. it obviously consists of roughly 4×15 the presently designed AMANDA array, leading to an "effective" volume of $\sim 6 \times 10^8$ m^3. Importantly, the characteristics of the detector, including threshold in the GeV-energy range, are the same as those of the AMANDA array module.

2. the $1 + 7 + 7$ supermodule configuration, looked at as a whole, instruments a 1 km^3 cylinder with diameter and height of 1000 m

with optical modules. High-energy muons will be superbly reconstructed as they can produce triggers in 2 or more of the supermodules spaced by large distance. Reaching more than one supermodule (range of 250 m) requires muon energies in excess of 50 GeV. We note that this is the energy for which a neutrino telescope has optimal sensitivity to a typical E^{-2} source (background falls with threshold energy, and until about 1 TeV little signal is lost).
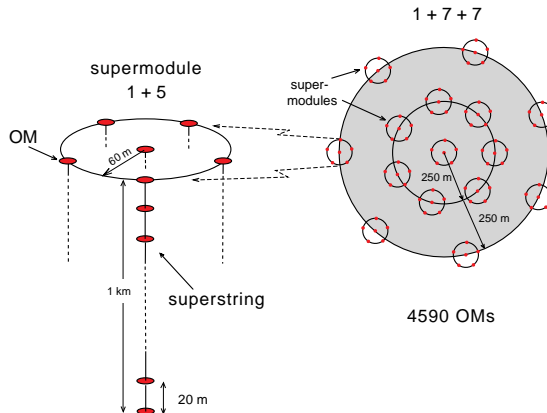

Fig. 3

Alternate methods to reach the 1 km scale have been discussed by Learned and Roberts[11].

What are the construction costs for such a detector? AMANDA's strings (with 10 OMs) cost $150,000 including deployment. By naive scaling the final cost of the postulated $1 + 7 + 7$ array of supermodules is of order $50 million, still below that of Superkamiokande (with $11,200 \times 20$ inch photomultiplier tubes in a 40 m diameter by 40 m high stainless steel tank in a deep mine). It is clear that the naive estimate makes several approximations over- and underestimating the actual cost.

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